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Laboratory Report

National Institute of Information and Communications Technology (NICT), Japan

Section 1: Laboratory Related Matters

- **[Cs primary frequency standards]**

The cesium fountain primary frequency standard NICT-CsF1 had been operated with a frequency uncertainty of 1.4×10^{-15}[1], and is being upgraded toward an operation at the 10^{-16} level. The 2nd fountain (NICT-CsF2) attaining the operation at the 10^{-16} level is under development. We have completed evaluations of most systematic frequency shifts and their uncertainties for CsF2 at the level below 5×10^{-16}, however the vacuum problem occurred in 2014. Currently, the system reconstructions and re-evaluations of the frequency shift are ongoing. As for microwave reference signal, the "cryocooler"-type cryogenic sapphire oscillator has started operation since 2014 toward a long-term continuous operation of the fountains.

- **[Optical frequency standards]**

NICT has been developing a ^{87}Sr lattice clock and a ^{115}In^{+} single-ion clock. The lattice clock based on the ^{87}Sr $^{1}S_{0}$-$^{3}P_{0}$ transition has been in operation since 2011. In 2015, the absolute frequency of the transition was measured to be 429 228 004 229 872.85 (47) Hz with the reduced uncertainty of 1.1×10^{-15}[2] with reference to the International Atomic Time (TAI). This spring, we operated the lattice clock for 10^4 s once in a week or more, for a half year. The steering of a stable hydrogen maser frequency according to the calibration by the lattice clock operation has demonstrated a highly stable and accurate time scale.

One of the major uncertainties of the absolute frequency measurement in 2015 was so-called dead time uncertainty between the TAI of five-day mean and one-month mean. With help of G. Petit in BIPM, we obtained the calibrations of the TAI frequency as the mean of the five days instead of the one-month mean available in Circular T. Using the five-day TAI calibration in 2015, the re-evaluation of the measurement has led to a 3×10^{-16} correction of the ^{87}Sr clock frequency. The total uncertainty was reduced to below 1×10^{-15}, in which 8.7×10^{-17} was attributed to the Sr optical frequency standard. The uncertainty in Sr system comprised of blackbody shift, lattice Stark shift, dc Stark shift and density shift. Recently, the dc Stark shift has been reduced considerably by irradiating UVLED light to windows. The re-evaluation of systematics is ongoing.

The quest for an ^{115}In^{+} single-ion clock continues with an expected inaccuracy in the order of 10^{-18} for the $^{1}S_{0}$-$^{3}P_{0}$ transition at 237 nm. We've succeeded in observing the quantum jump of this clock transition for the first time using a scheme of sympathetic cooling, where two ^{40}Ca^{+} ions are also trapped as coolant in a linear configuration. The state detection is possible using $^{1}S_{0}$-$^{3}P_{1}$ fluorescence with sufficient S/N. While absolute frequency of the clock transition was measured in two laboratories in Germany[3, 4], the two results have a fractional discrepancy of 1×10^{-14}. Hopefully, we will be able to demonstrate our measurement of this clock transition after reducing the spectral linewidth. The availability of state detection method can extend the single-ion In^{+} clock to a multi-ion clock, which is expected to break the stability limit of single-ion clocks.

- **[THz frequency standards]**

Frequency standards in THz domain (0.1-10 THz, wavelength 30um-3mm) are being developed. For the precise frequency measurements, we have developed a THz frequency counter based on a photocarrier-THz comb in a photoconductive antenna illuminated by second harmonics of a 1.5um femtosecond pulse laser. Its measurement precision, which is better than $10^{-17,}$ was confirmed in 0.1-0.65THz region[5]. Such THz comb technology was applied to an innovation of a THz-to-microwave synthesizer, which served as a novel THz frequency divider[6]. We started to extend the measurable range up to around 3THz by heterodyning with a microwave standard using a superlattice harmonic mixer. We have also developed a ultra-stable and widely-tunable THz continuous wave (cw) synthesizer by the photomixing of two lasers coupled into a uni-traveling carrier photo diode (UTC-PD). It generated cw-radiation at an arbitrary frequency from 0.1THz to 3THz with the instability of less than 1mHz in 1000s averaging time. This technology has opened a new window for distributing a THz frequency reference to a remote site via an optical fiber network. Another method of THz reference transfer through an optical fiber was also demonstrated with 4 x 10^{-18} accuracy at 0.3THz, using a combination of frequency-comb-based THz-to-optical and optical-to-THz synthesizers.

- **[CSAC (Chip Scale Atomic Clock)]**

Activities related to chip-scale atomic clocks have been initiated in April 2016 as an application of atomic frequency standards to the era of IoT (Internet of Things). Together with reduced power consumption, our target is to miniaturize the setup so that it becomes possible to install it into mobile systems.

- **[Advanced T&F transfer technique]**

NICT is leading the development of TWSTFT carrier-phase (TWCP) technique and has shown excellent results[7]. Aiming the dissemination of its high measurement precision in 10^{-13}, NICT has started the development of a new TWSTFT modem in 2016.

- **[Join to the ACES satellite mission]**

ACES (Atomic Clock Ensemble in Space) is the ESA space mission, which is scheduled for flight onboard the international space station in FY 2017[8]. It aims to conduct several precision tests in fundamental physics such as measurement of Einstein's gravitational frequency shift. The measurement will be performed by a frequency transfer link in the microwave domain (MWL). MWL compares the ACES frequency reference with respect to a set of ground clocks. To accomplish this mission, a total of seven MWL ground terminals (GTs) will be distributed to metrological institutes which have an accurate frequency standard and a frequency transfer link. NICT was selected as one of the deployment sites for the MWL GT and will contribute to ACES in cooperation with University of Tokyo, RIKEN and NMIJ. The construction of two platforms for MWL GT was completed on the rooftop of the NICT building during FY 2015. The MWL GT installation is planned for FY 2017.

- **[VLBI for frequency transfer]**

NICT is investigating potential of VLBI as one of the tools for advanced time and frequency transfer. The GALA-V project consists of broadband VLBI system with transportable small diameter VLBI stations. Frequencies between atomic time standards used at transportable VLBI stations are compared by VLBI observation. Disadvantage of small diameter antenna is compensated by 1) enhancement of SNR and delay precision by broadband observation, and 2) joint observation with high sensitivity VLBI station as intermediate station. Observation frequency range of GALA-V (3-14GHz) is designed to be compatible with that of VGOS (VLBI Global Observing System), which is next generation geodetic VLBI system being promoted by IVS. Joint VLBI observation with VGOS stations will enable frequency transfer experiments between two transportable stations. Original broadband feed systems were developed by NICT for Cassegrain type Kashima 34m diameter VLBI antenna and small diameter antennas. These new receiver systems have enabled VLBI observation with unprecedented broad (3-14GHz) frequency range. Another new technology introduced in this project is "RF-Direct-Sampling" technique, which converts analog radio signal to digital data by using high speed A/D at 16GHz sampling rate without analog frequency conversion. Four bands of signals with 1 GHz band width at specified radio frequency is extracted by digital signal processing, and the data is acquired to high speed recording system through 10G-Ethernet interface. This RF-Direct-Sampling technique has a big advantage at stable phase relation between the signals of each bands. Since precise group delay observable is obtained by linear phase gradient over broad frequency range, phase distortion caused by the signal transmission line from the radio telescope to the recording system has to be calibrated. Linear phase characteristics is the key feature to measure precision group delay with broadband signal. Conventionally, phase calibration signal (Pcal) has been used to calibrate phase characteristics of the system, but special care is needed to keep phase stability of the Pcal device itself. Our RF-Direct-Sampling technique can keep stable phase relation by digitizing signal without analog frequency conversion. A broadband test VLBI experiment between Kashima 34m and Japanese VGOS station (Ishioka 13m station of GSI- Geospatial Information Authority of Japan) has demonstrated that the broadband VLBI can achieve sub-pico second delay measurement with 1 second of integration.

Two small VLBI stations: MARBLE1 and MARBLE2 have been installed at National Institute of Metrology in Japan (NMIJ) in Tsukuba and NICT-HQ in Koganei, respectively. A series of broadband VLBI experiments with these three stations have been conducted since the beginning of 2016. UTC(NICT) and UTC(NMIJ) have been compared by VLBI observation and ppp-analysis of GNSS observation. The two frequency transfer technique shows consistent results. Further improvement of frequency transfer accuracy is being pursued with a scope of intercontinental VLBI frequency transfer experiment in the near future.

■ **[Japan Standard Time and dissemination services]**

The time difference between UTC(NICT) and UTC has been kept almost within ±20 ns for the last 1 year. NICT has 29 high-performance Cs clocks and 7 H-masers, and UTC(NICT) is generated from the H-maser's frequency regularly steered by an averaged frequency of 18 high-performance Cs clocks at Koganei-HQ. Other Cs clocks are in operation at two LF stations and at the Kobe JST sub-station. For the construction of distributed generation system of Japan Standard Time, timescale generation sub-system including atomic clocks and time link systems have been installed and calibrated. Currently, preliminary operation tests for the sub-systems at Kobe are in progress.

Regarding dissemination, renewal of transmitting equipment of both LF stations has been carried out. In the NTP servers, daily access was over 2 billion in October 2016.

■ **[Regular time link via satellites]**

NICT has been operating two Septentrio PolaRX receivers and Dicom GTR50 for a network of international time links. The receivers were calibrated as APMP G1 by BIPM in April 2016. For the JST distributed generation system under development, we constructed a GPS real-time common-view (RTCV) time link between NICT-HQ and Kobe branch. GPS RTCV is also used to monitor the clocks located at two LF stations.

As for the TWSTFT, Asia-Europe link has been suspended since 2014 because there is no available satellite now. Details of the international observation is described in Section 2. Domestic observation is regularly carried out by using the Eutelsat 172A satellite between NICT-HQ and two LF stations.

■ **[Structure of Staff and Contact Persons]**

Table 1 shows the contact persons of TCTF activity group.

Table 1 Contact persons in the field of time and frequency standards at NICT

Position and Duty	Name	e-mail address
AERI, Director General	Dr. Kazumasa TAIRA	k.taira@nict.go.jp
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Japan Standard Time Group	Mr. Kuniyasu IMAMURA Mr. Haruo SAITO	kei@nict.go.jp saito@nict.go.jp
Atomic Frequency Standards Group	Dr. Tetsuya IDO	ido@nict.go.jp
Space-Time Measurement Group	Dr. Ryuichi ICHIKAWA	richi@nict.go.jp
Space-Time Measurement Group at Kashima	Dr. Mamoru SEKIDO	sekido@nict.go.jp
Contact Persons regarding APMP	Dr. Yasuhiro KOYAMA Dr. Mizuhiko HOSOKAWA	koyama@nict.go.jp hosokawa@nict.go.jp

AERI: Applied Electromagnetic Research Institute

STSL: Space-Time Standards Laboratory

Section 2: CIPM MRA Related Activities

■ **[Present Status for Signatory of the MRA]**

NICT, NMIJ/AIST, CERI, and JEMIC are the signatory institutes to the Global MRA in Japan. NICT is the member institute of CCTF belonging to CIPM, TCTF and TCQS of APMP.

- **[International Comparison Activity]**

NICT has organized the Asia-Pacific Rim TWSTFT link, currently utilizing the satellite Eutelsat 172A. Time transfer is performed once every hour. Additionally, in 2010 an Asia-Hawaii link was established using the same satellite. The Hawaii station was established as a monitoring station for the QZSS project. After that, time transfers between NICT, TL, KRISS and USNO had been performed once every hour by combination of the two links: Asia-Hawaii and USNO-Hawaii. Because the QZSS project came to an end, the Hawaii station will be closed. Time transfer between Asia and USNO was discontinued in August 2016 with the completion of the QZSS project. However, time transfer in Asia is being conducted continuously.

The Asia-Europe TWSTFT link had been cooperatively constructed by major T&F institutes in Asia; NICT, TL, NIM, NTSC, KRISS, NPLI, and two European institutes; PTB and VNIIFTRI. The link had been established by the satellite IS-4 until the beginning of 2010. However, due to the malfunction of IS-4 it was switched to the satellite AM-2 in October 2010. Due to the end of lifetime of the AM-2 satellite, the link was terminated in November 2014. After that, a new satellite named AM-22 has been used for the Asia-Europe link. Unfortunately, NICT and TL are out of the coverage area of AM-22. Other institutes, NTSC, NIM, KRISS, VNIIFTRI and PTB participate in the link.

- **[Status of Management System]**

NICT was certified to be in accordance with the ISO/IEC 17025 for the carried-in frequency calibration system by National Institute of Technology and Evaluation (NITE) in March 2001 and obtained accreditation of ISO/IEC 17025 from NITE on January 31, 2003. Thereafter, NICT additionally obtained accreditation of ISO/IEC 17025 for the remote frequency calibration system and the time scale difference calibration system from NITE on May 2, 2006 and September 30, 2011 respectively. The Calibration Measurement Capability (CMC) of carried-in frequency calibration system was changed to 5×10^{-14} in April 2007, and the Measurable range of carried-in frequency calibration was expanded from 1Hz to 100MHz in September 2011. NICT underwent surveillance conducted by NITE in February 2013 and renewed the IAJapan certificate dated April 26, 2013. The on-site peer was conducted in March 2016 and NICT has obtained the approval from NITE for the continuation of the accreditation of ISO/IEC 17025.

- **[Activities Concerning CMCs Submission]**

The first CMC table was approved and registered in the KCDB in August 2005. The revised CMC table was also submitted and registered in the KCDB in November 2009. The latest CMC table was reviewed in July 2015, and was approved and registered in the KCDB in October 2016.

Section 3: International and Regional Cooperation

To conduct and construct the TWSTFT networks in the Asia Pacific region, NICT has bilateral cooperation with many foreign institutions.

Section 4: Activities relevant to APMP's "Focus Areas"

No related activity.

Section 5: Future Plans, Priorities and the Role of APMP

- **[New scheme of international GNSS calibration]**

NICT has already prepared a GNSS calibration system for the APMP group-2 laboratory trips as a group-1 laboratory in late FY 2015. This calibration network scheme for the international time link is planned by BIPM. The system was installed at NICT headquarter and an internal evaluation has been performed by comparing with other NICT receivers. The first calibration of the NICT GNSS calibrator has already been completed in April 2016 using the golden system calibration of BIPM. We are now preparing to start Group 2 trips. In addition, we are contributing to the MEDEA (Metrology – Enabling Developing Economies in Asia) project which is conducted by PTB in order to support Group 2 trips. We are also verifying the calibration procedure by actual calibration trips in NICT branches with this system.

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